Formation of the Galactic disk globular clusters in early dissipative minor merging

Kenji Bekki
School of Physics, University of New South Wales, Sydney 2052, Australia

and

Masashi Chiba
National Astronomical Observatory, Mitaka, Tokyo, 181-8588, Japan

ABSTRACT

The origin of metal-rich, highly flattened, and rapidly rotating disk globular cluster system in the Galaxy is one of longstanding issues in the context of the Galaxy formation. Our numerical simulations suggest a new "two-fold" scenario that the disk globular clusters are firstly formed in the high-pressure, dense central region of a gas-rich dwarf galaxy, as induced during the tidal interaction with the pre-existing, young thin disk of the Galaxy, and then dispersed into the disk region owing to the final tidal destruction of the merging dwarf. We also demonstrate that spatial distribution, total number, and metallicity distribution of the clusters formed in this minor merging depend on the mass ratio of the host to dwarf galaxy and the orbital configuration of merging. Based on these results, we discuss whether a minor merging event about 10 Gyr ago can explain both the Galactic thick disk and the disk globular clusters. Several other implications for the possible relation between the properties of disk galaxies and their disk globular clusters are also discussed.

Subject headings: (Galaxy:) globular clusters: general – Galaxy: abundance – Galaxy: evolution – Galaxy: halo – Galaxy: structure

1. Introduction

The globular cluster system of the Galaxy has been traditionally divided into two distinct populations: Metal-poor, roughly spherical, slowly rotating "halo" population and metal-rich, flattened, rapidly rotating "disk" one (e.g., Zinn 1985, 1991; Armandroff 1989,

1993; van den Bergh 2000). Recent more detailed studies of the disk globular clusters have however suggested that the distinction between the two populations may not be so obvious (e.g., Richtler et al. 1994; van den Bergh 2000), and furthermore that the metal-rich globular clusters are associated with the Galactic bulge rather than the disk (e.g., Minniti 1995; D. Forbes et al. 2001, in preparation). Physical properties of the disk globular clusters, such as structure, kinematics, and metallicity distribution, are considered to provide valuable information on the Galactic early dynamical evolution (Zinn 1991). Owing to the similarity in kinematics, structure, and abundance between the Galactic thick disk and the disk globular clusters, the physical relationship between these two Galactic components have been particularly discussed (e.g., Armandroff 1993; Norris 1993).

Armandroff (1993) suggested that physical processes responsible for the formation of the disk globular clusters include: (1) secular scattering of disk stars and clusters, (2) dynamical heating of the pre-existing thin disk by merging of one or more dwarf galaxies (Quinn & Goodman 1986; Quinn, Hernquist, & Fullagar 1993), (3) gaseous dissipation during tidal encounter between the pre-existing thin disk and satellites (Ashman & Zepf 1992), and (4) dissipative collapse of the Galactic disk (Burkert, Truran, & Hensler 1992). However, there have been yet no further theoretical studies which investigate how the disk globular clusters are formed and whether their dynamical and chemical properties can be explained by a scenario based on the above physical process(es). Therefore it still remains uncertain which physical process is the most dominant mechanism for the formation of the disk globular clusters (Armandroff 1993).

The purpose of this paper is to propose a new "two-fold" mechanism in which the disk globular clusters are first formed by dissipative tidal interaction between a gas-rich dwarf galaxy and the pre-existing, Galactic thin disk, and then dispersed into the Galactic disk region owing to tidal stripping of the merging dwarf. We show that the high-pressure, dense central region of a merging dwarf, which is induced by the Galactic tidal force, can be the site for the formation of the disk globular clusters, because the high pressure of warm interstellar gas ($P_{\rm g} > 10^5$ $k_{\rm B}$: $k_{\rm B}$ is Boltzmann's constant) can induce global collapse of giant molecular clouds and form massive compact star clusters corresponding to globular clusters (Harris & Pudritz 1994; Elmegreen & Efremov 1997). Based on numerical simulations, we investigate whether this minor merging event can develop such a high pressure region inside a gas-rich dwarf. The present study is the first to demonstrate the detailed predictions of a certain formation scenario, where we base on a "two-fold" mechanism, to assess whether the model reproduces not only metallicity distribution (e.g., Zinn 1985) but also orbital properties of the disk globular clusters (e.g., Dinescu et al. 1999). Therefore we believe that the present study can shed new light on the formation of the Galactic globular clusters.

2. Model

We consider a dissipative minor merger between a large disk with its dynamical structure similar to that of the Galaxy and a gas-rich dwarf galaxy represented by a small disk. Since our numerical methods for modeling chemodynamical evolution of this dissipative merger, using the TREESPH codes for hydrodynamical evolution, have already been described by Bekki & Shioya (1998) and by Bekki (1995), we give only a brief review here. We use the exponential disk model of Fall & Efstathiou (1980) with the dark-halo-to-disk mass ratio equal to 4 both for the larger and smaller disks. The total mass and the size of the larger (smaller) progenitor disk are $M_{\rm d}$ ($m_2 \times M_{\rm d}$, where m_2 is the mass ratio of two disks) and $R_{\rm d}$ (${m_2}^{1/2} \times R_{\rm d}$), respectively. From now on, all the masses and lengths are measured in units of $M_{\rm d}$ and $R_{\rm d}$, respectively, unless otherwise specified. Velocity and time are measured in units of $v = (GM_{\rm d}/R_{\rm d})^{1/2}$ and $t_{\rm dyn} = (R_{\rm d}^3/GM_{\rm d})^{1/2}$, respectively, where G is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_{\rm d} = 6.0 \times 10^{10}$ $M_{\odot}$ and $R_{\rm d} = 17.5$ kpc as fiducial values, then $v = 1.21 \times 10^2$ km s^{-1} and $t_{\rm dyn} = 1.41 \times 10^8$ yr, respectively. Here, for the sake of clarity in the demonstration of our proposed scenario, we show the case that *only the dwarf galaxy has a gaseous component*; our experiments indicate that the presence of gas in the larger, Galactic disk does not affect our conclusion. We set the gas mass fraction of the smaller disk as 0.1. An isothermal equation of state is used for the gas with temperature of 7.3×10^3 K (corresponding to sound speed of 10 km s^{-1}). Guided by the observed metallicity-luminosity relation for dwarf galaxies, [Fe/H]=$-3.43(\pm0.14) - 0.157(\pm0.012) \times M_V$ (e.g., Côté et al. 2000), where M_V is the V-band magnitude of a dwarf, we give initial metallicity to each gaseous particle. For the model with $m_2 = 0.02$, the corresponding initial metallicity [Fe/H] is about -0.82. By changing the mass ratio m_2, and orbital eccentricity ($e_{\rm orb}$), pericentric distance ($r_{\rm p}$), orbital inclination of the dwarf's orbit (θ), we investigate the parameter dependences of physical properties of forming globular clusters. We present mainly the results for our fiducial model with m_2=0.02, $e_{\rm orb}$=0.5, $r_{\rm p} = 0.75R_{\rm d}$, and $\theta = 30^{\circ}$.

We adopt the following two different star formation laws to convert gaseous particles into either globular clusters or field stars. For globular clusters, we adopt the formation model by Harris & Pudritz (1994), in which interstellar gaseous pressure (P_g) in star forming regions of a galaxy can drive collapse of pressure confined, magnetized self-gravitating proto-cluster molecular clouds and form compact clusters, if P_g is larger than the surface pressure ($P_{\rm s}$) of the clouds:

$$P_{\rm g} \geq P_{\rm s} \sim 2.0 \times 10^5 k_{\rm B}. \tag{1}$$

In our simulations, a gas particle is converted into *one* new cluster if the gas pressure is larger than $P_{\rm s} = 2.0 \times 10^5 k_{\rm B}$. Although we cannot investigate the detailed physical processes

of cluster formation in the present *global* (from $\sim$ 100 pc to 10 kpc scale) simulation, we expect that the adopted phenomenological approach enables us to identify the plausible formation sites of globular clusters. For field stars, we adopt the Schmidt law (Schmidt 1959) with the exponent of 1.5 (Kennicutt 1989). Although this model for star formation is based on the observed *current* star formation law in the Galactic disk and dwarfs, which may not be simply applied to high redshifts, its details do not affect the derived results for forming clusters.

3. Results

Figure 1 and 2 describe how the Galactic disk globular clusters are developed and spatially distributed in the fiducial minor merger model. As the dwarf passes by the pericenter of its orbit, the strong tidal field of the Galaxy greatly distorts the dwarf's morphology to induce efficient energy dissipation in the shocked gaseous regions. As a result, gas particles having an initially exponential spatial distribution inside the dwarf are efficiently transferred to the central region of the dwarf, where the gaseous density and pressure are made high enough to trigger the globular cluster formation (Figure 2). Young globular clusters are formed preferentially in the dwarf's central region with high pressure and density (T=0.56 Gyr in Figure 1), and they are confined inside the dwarf during the early stage of this merging event (T=2.26). As the dwarf spirals into the center of the Galaxy owing to dynamical friction and is consequently destroyed by the strong tidal field (T = 2.82), the globular clusters are violently dispersed into the Galactic disk region. The clusters removed from the dwarf appear to retain the orbital angular momentum of the progenitor dwarf with respect to the Galaxy. Therefore, the cluster system shows moderate rotation and highly flattened spatial distribution even after the dwarf destruction and be identified as "disk globular clusters" (T = 3.38, 3.95). Thus the above simulation demonstrates that the disk globular clusters are first formed in the central region of the dwarf during the tidal encounter of the two disks, then dispersed around the plane of the Galaxy after the dwarf's destruction.

Figure 3 shows that the metallicity distribution of the simulated disk globular clusters has the peak at [Fe/H] ~ -0.7 with the mean metallicity of -0.58, that is 1.7 times larger than the initial metallicity of the dwarf. This increase in metallicity is due to gaseous chemical evolution of the starbursting dwarf. Here, we remark that if the dwarf has already retained globular clusters which are not formed by the current mechanism and if they are simply dispersed after this merging event, their typical metallicity is estimated as [Fe/H]=-1.45 using the observed host luminosity vs. cluster metallicity relation (e.g. Côté

et al. 2000); such a scenario without taking into account newly formed clusters fails to reproduce the observed metallicity of the disk globular clusters. Thus, our results imply that gaseous dissipation during tidal deformation of a dwarf, and subsequent star formation and chemical evolution inside it can play an important role in the formation of metal-rich disk globular clusters. The derived peak metallicity depends on m_2 such that the peak value is larger for larger m_2. This implies that the dwarf mass should be in a certain range in order to reproduce the observed peak value of metallicity distribution of the Galactic disk globular clusters (~ -0.6, e.g., Zinn 1991).

As is shown in Figure 3, only a small fraction of the simulated globular clusters (20%) have orbital eccentricities (e) smaller than 0.3 (i.e., more circular orbits) and the mean eccentricity is estimated to be 0.52. This result is in disagreement with the recent observational result by Dinescu et al. (1999) which suggests that a fairly large fraction of the Galactic disk globular clusters show nearly circular orbits ($e < 0.3$). A possible reason for this discrepancy is that many of high-e disk globular clusters obtained here are preferentially destroyed by the Galactic tidal field, because such clusters pass by the central region of the Galaxy, so that they are missing at the present epoch. Also, there may exist some observational bias in the selection of cluster sample; the Dinescu et al. result is based on a small number of clusters with available proper motions.

The above results are obtained from our fiducial model, but general properties of globular clusters formed by the current mechanism are quite diverse depending on the merger parameters. Figure 4 summarizes the derived diversity. Firstly, the spatial distribution of disk globular clusters is more centrally concentrated and more spherical for the model with smaller pericentric distance ($r_{\rm p}$) and larger orbital eccentricity ($e_{\rm orb}$) (panel a). Secondly, the distribution is less centrally concentrated and more spherical for the model with higher degree of the dwarf's orbital inclination (panel b). Thirdly, globular clusters are less efficiently formed and rather centrally concentrated in the retrograde minor mergers (panel c). This is essentially because tidal disturbance in retrograde merging is so weak that the developed globular clusters can not be tidally stripped so readily. Fourthly, formation efficiency of disk globular clusters and the mean metallicity are higher, and the spatial distribution is more centrally concentrated, for the model with larger m_2 (panel d) — such clusters may correspond to the "bulge" globular clusters. This result furthermore implies that a disk galaxy with a thicker disk and/or a bigger bulge may hold a larger number of more metal-rich and more centrally concentrated disk (or bulge) globular clusters. This is essentially because a merger with larger m_2 can create both a thicker disk (Bekki & Shioya 2000) and a larger number of more metal-rich globular clusters (this study) owing to stronger tidal disturbance. Taking into account the above dependence of the result on model parameters, we stress that the nature of disk globular clusters in various disk galaxies

may provide us valuable information on their past dynamical histories of dissipative minor merging.

4. Discussion and conclusion

4.1. Advantages and disadvantages of the present model

The present numerical study has first demonstrated that gaseous pressure of a gas-rich dwarf tidally interacting and merging with the Galactic disk can become so high ($> 10^5\ k_{\rm B}$) as to induce global collapse of giant molecular clouds, which are considered to be progenitor objects of disk globular clusters. Our numerical simulations have also demonstrated that if the orbit of the dwarf is nearly coplanar with respect to the Galactic plane, globular clusters formed by the present mechanism show both highly flattened density distribution and rapid rotation. Based on these results, we suggest that the observed structural, kinematical, and chemical properties of the Galactic disk globular clusters can be understood in terms of orbital configuration and metal abundance of gas-rich dwarfs which merge with the Galactic disk. Since galaxy merging is considered to be important for the formation of thick disks (e.g., Quinn et al. 1993) and bulges (e.g., Barnes & Hernquist 1992), the present study implies the existence of some correlation between the Hubble morphological sequence and physical properties of disk globular clusters. Thus our scenario has advantages not only in explaining some of fundamental properties of the Galactic disk globular clusters but also in providing clues to the better understanding of physical relationship between formation of disks and globular clusters.

However, it is not so clear whether the presented scenario can explain the following three aspects of the Galactic disk globular clusters: (1) distribution of orbital eccentricities (e), (2) three dimensional spatial distribution, and (3) metallicity distribution. The present study predicts that the fraction of nearly circular orbits ($e < 0.3$) is only ~ 20 % whereas recent observations (Dinescu et al. 1999) showed it to be 100 %, although this estimate is based on only two clusters with [Fe/H] > -0.8 in the Dinescu et al. sample — the selection of the cluster sample is biased in terms of availability of proper motions. Nonetheless, if many of disk globular clusters are characterized by low-e orbits, a fairly large fraction of high-e clusters, formed by the present mechanism ~ 10 Gyr ago, should have been destructed by some mechanisms (i.e., some high-e clusters disappear by the present epoch), so that the present model can be still consistent with the observation by Dinescu et al. (1999). There are two proposed mechanisms for the destruction of globular clusters: (1) bulge shocking (e.g., Aguilar, Hut, & Ostriker 1988) and (2) spiral-in to the Galactic center via dynamical friction and the resultant destruction of globular cluster and the formation

of the Galactic nucleus (Tremaine, Ostriker, & Spitzer 1975).

Aguilar et al. (1988) demonstrated that since the gravitational shocks due to the central bulge of the Galaxy are very efficient in destroying clusters on highly radial orbits, clusters passing through the central 2 kpc can be quickly destroyed by the Galactic central tidal field. The time scale for a globular cluster to spiral in to the Galactic nucleus owing to dynamical friction can be estimated (e.g., Bekki & Couch 2001),

$$t_{\rm fric} = 7.8 \times 10^9 \left(\frac{r_i}{2{\rm kpc}}\right)^2 \left(\frac{V_c}{200{\rm km\ s^{-1}}}\right) \left(\frac{10^6 M_{\odot}}{M_{\rm cl}}\right) \ {\rm yr}. \qquad (2)$$

Here we neglect the $\ln \Lambda$ term (~ 6.6 for a plausible set of parameters), and $r_{\rm i}$, $V_{\rm c}$, and $M_{\rm cl}$ are the initial radius from the Galactic center, circular velocity, and mass of the cluster, respectively. Therefore, *if a disk globular cluster formed $\sim$ 10 Gyr ago can pass through the central 2 kpc or be initially within the central 2 kpc, it cannot be observed at the present epoch owing to tidal destruction and spiral-in to the Galactic nuclei.* Based on these simple theoretical arguments, we can investigate what fraction of the simulated disk clusters with $e > 0.3$ disappear owing to the above mechanisms.

We choose the simulated clusters with $e > 0.3$ and investigate whether or not these can pass through the central 2 kpc of the Galaxy. We find that among 56 clusters with $e > 0.3$, 39 ($\sim$ 70 %) can pass through the central 2 kpc within several orbital periods. This implies that most of the simulated disk clusters cannot survive from tidal shocking of the Galactic bulge (or spiral-in to the nucleus) and thus are not identified as globular clusters at later epochs. Therefore, we can expect that the fraction of disk globular clusters (formed earlier) with $e < 0.3$ at the present epoch can be $\sim$ 53 % in the simulation. Further measurements of proper motions of many more disk clusters, by next-generation astrometric satellites such as FAME and GAIA, are required to assess our prediction.

The observed disk globular clusters are confined inside about 9 kpc from the Galactic center and about 3 kpc from the Galactic plane (Zinn 1985). It is an important test whether or not the present model can reproduce this observational result. Figure 5 shows that the simulated clusters are confined inside about 8 kpc from the Galactic center and about 2 kpc from the Galactic plane, which is basically consistent with observations. Figure 5 also shows that even if we remove the high-e clusters (with $e > 0.3$) having the pericentric distances smaller than 2 kpc (i.e., those not observed at the present epoch owing to tidal destruction from the Galactic bulge), the spatial distribution remains almost the same. Therefore we can say that the present scenario is consistent at least qualitatively with the observed spatial distribution of the disk globular clusters.

What we should emphasize here is that observational data show that many globular

clusters are currently within 2 kpc of the Galactic center. The existence of these bulge globular clusters appears to be inconsistent with the results by Aguilar et al. (1988) and thus implies that the above discussion is not so plausible. We however consider that these bulge clusters may exits owing to the following reasons: (1) Their orbits are circular with $e < 0.3$, (2) these clusters with low e are on the way of disappearance in a long time scale, (3) these clusters are more tightly bound, having high densities and small radius, and (4) these have just arrived at the central 2 kpc from the outer region of the Galaxy owing to dynamical friction (i.e., there is not enough time for the Galactic central tidal field to destroy these clusters). Because of the lack of extensive observations on the physical properties (e.g., orbits, proper motion, and structures) of the central bulge clusters, it is difficult to determine why the Galactic bulge clusters are now observed (i.e., which of the above four explanations is more plausible) and whether the results by Aguilar et al. (1988) can be observationally confirmed. Thus we suggest that the validity of the present scenario, which requires later destruction of high e globular clusters by the Galactic central tidal field in order to explain the observed nature of the disk globular clusters, can be assessed by future observations on the bulge globular clusters.

Since the metallicity distribution of globular clusters reflects the chemical evolution of the Galaxy and the Galactic building blocks (e.g., van den Bergh 2000), it is also an important test for any viable theories of the Galaxy formation and globular cluster formation. The present study shows that irrespectively of model parameters, the metallicity distribution of the simulated clusters is sharply peaked. On the other hand, observational studies (e.g., Zinn 1985), showed that the metallicity of disk clusters with [Fe/H] > -0.8 is rather broadly distributed with the peak metallicity around [Fe/H] ~ -0.6. One possible interpretation of this inconsistency is that owing to some observational errors in the metallicity scale of globular clusters (e.g., Sarajedini 1999), the observed metallicity distribution of disk globular clusters is smeared out, even if the actual distribution is sharply peaked. In order to assess the validity of this possible interpretation, we examine an average error in [Fe/H] of disk globular clusters with [Fe/H] > -0.8 for the sample of Zinn (1985) using Table 6 of Zinn & West (1984), and found that it is ~ 0.19 dex. This result suggests that if we convolve a Gaussian with a dispersion of 0.2 dex (derived above) to a metallicity distribution with the sharp peak of -0.6 dex, we can anticipate that the resultant metallicity is rather broadly distributed ranging from -0.8 to -0.4. This result implies that the above inconsistency between the present model and observations is not necessarily a serious problem of the present scenario of the Galactic disk globular cluster formation. In this regard, further, more accurate metallicity measurements of metal-rich globular clusters are needed to arrive at their true metallicity distributions (e.g., Carretta et al. 2001; Cohen et al. 1999).

4.2. An alternative scenario

We have not presented the effect of a gaseous component in the Galactic disk on the formation of disk globular clusters, as we focus on dwarf galaxies as the sites of forming globular clusters. Dissipative merging has already been suggested to induce the formation of globular clusters *inside the Galactic gas disk* (Ashman & Zepf 1992), and the detailed processes are now being investigated by Bekki & Chiba (2001, in preparation). This alternative and still attractive scenario might well have the following advantages and disadvantages in explaining structure, kinematics, and chemical properties of disk globular clusters (Bekki & Chiba 2001, in preparation).

Firstly, irrespectively of orbital configurations of dissipative merging, the globular clusters formed inside the Galactic gas disk can show fairly flattened density distribution and rapid rotation (for models with a fixed mass ratio of merging two galaxies). The formation process which is independent of merger orbital configuration is attractive in the sense that structural and kinematical properties of disk globular clusters in external disk galaxies are basically quite similar to one another. Secondly, in order to reproduce the observed mean metallicity of disk globular clusters, dissipative merging should occur *only when the Galactic disk has the metallicity of* ~ -0.6 *(i.e., the Galaxy is very young, just after the formation of the Galactic stellar halo).* It is not clear at all why such a merging occurs only one time and at such a preferred epoch. If a couple of dissipative merging events are involved in the formation of globular clusters, then the resultant metallicity distribution would show multiple peaks with variously different values, which is totally inconsistent with observations.

Thirdly, even if dissipative merging that forms disk globular clusters occurs at a preferred epoch, the metallicity gradient of the gas-rich, young Galactic disk at this merging epoch should be very different from that of the present-day Galactic disk. To be more specific, if the young Galactic disk has the mean metallicity of [Fe/H] ~ -0.6 at the epoch of merging while having the metallicity gradient being exactly the same as that of typical present-day disks derived by Zaritsky et al. (1994) and if globular clusters are formed inside the entire region of the gas disk, the expected metallicity of disk globular clusters can range from [Fe/H] $= -1.1$ to -0.1. This appears to be inconsistent with observations and thus the gaseous metallicity gradient of the Galactic disk at the epoch of merging should be enough small.

4.3. A physical relationship between the Galactic thick disk, halo globulars, and disk ones

Previous numerical studies have demonstrated that dynamical heating of the pre-existing Galactic young thin disk by minor merging of dwarf galaxies can create the thick disk component (e.g., Quinn & Goodman 1986; Quinn, Hernquist, & Fullagar 1993). The present results combined with these previous ones raise the following two questions: (1) Is just one minor merging event responsible both for the thick disk formation and for the disk globular formation? (2) When did such minor merging occur? Quillen & Garnett (2000) re-examined the age-velocity dispersion relation in the solar neighborhood and found that there is an abrupt increase in the vertical velocity dispersion of the Galactic stellar disk at an age of 9–10 Gyr. They suggested that this abrupt increase can be explained not by any gradual and long-term scattering of disk stars by spiral arms but by minor merging occurred 9–10 Gyr ago. If this minor merging also results in the formation of disk globular clusters, the age of the disk globular clusters should be 9–10 Gyr. Although it is yet uncertain in the age estimate of each disk globular cluster (e.g., Rosenberg 2000), refining the ages of clusters will settle the above two issues, or assess the validity of the proposed minor merging scenario for the formation of the thick disk and disk globular clusters.

The origin of the observed dichotomy between the Galactic halo and disk globular clusters is one of unresolved problems of the Galaxy formation. We propose that the halo globular clusters are formed by multiple interaction/merging of hierarchically clustered subgalactic clumps or dwarf galaxies, perhaps seeded by CDM subhalos, *prior to disk formation*, whereas the disk globulars are formed by a minor merging of a dwarf with the Galaxy *subsequent to* the first thin disk formation. Recent numerical simulations based on a hierarchical clustering scenario (e.g., Bekki & Chiba 2001) have demonstrated that metal-poor stars observed in the Galactic halo were formed initially within subgalactic clumps, which are developed from initial density fluctuations at high redshifts, and then dispersed into the Galactic halo region when clumps are disrupted by tidal stripping. If clumps contain globular clusters, perhaps formed at the epoch of clump formation, and if these clumps merge violently with each other at random orientation of orbits, then these globular clusters will also be widely spread over the halo region during interaction/merging. The aftermath may represent the halo globular cluster system, having spherical distribution and very small amount of rotation.

Just after the end of such violent merging events, the first thin disk component has been at place in the simulated model (Bekki & Chiba 2001). Then, some dwarf galaxies, having large orbital angular momentum with respect to the proto-Galaxy, may arrive at the later epoch. Such dwarfs eventually interact with the first Galactic thin disk, accompanying

the tidal deformation. If the initial orbits of these later merging dwarfs are nearly co-planer as examined here or if the orbits are made more co-planer owing to dynamical friction from disk stars, then the globular clusters that are formed during tidal interaction can be dispersed near the disk plane after tidal stripping from the dwarfs. Thus we suggest that the dichotomy between the halo and disk globular clusters may be caused by the difference in the merging epoch of subgalactic clumps or dwarf galaxies, depending on their initial angular momentum; cluster populations may be distinguished whether the merging occurred either before or after the disk formation.

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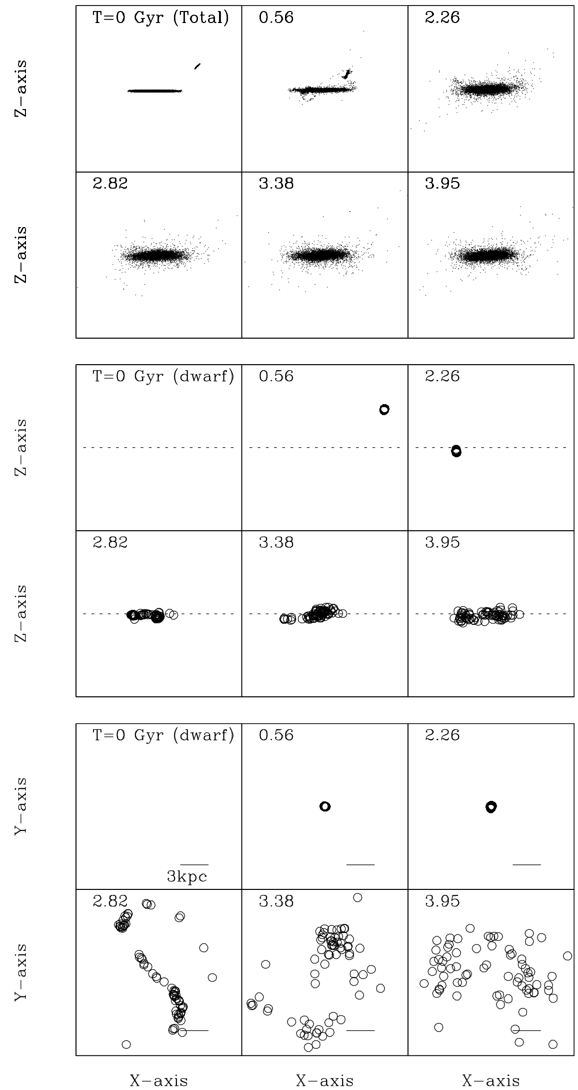

Fig. 1.— *Top six*: Mass distribution of the fiducial merger model projected onto x-z plane. All components except dark matter are plotted for T = 0, 0.56, 2.26, 2.82, 3.38, and 3.95 Gyr. Here T represents the time that has elapsed since the two disks begin to merge. A frame measures 105 kpc on a side for each panel. *Middle six*: Mass distribution of globular clusters (represented by open circles) projected onto x-z plane in the fiducial model. In total, 71 globular clusters are formed in this model. The initial disk position and the size are represented by dotted lines and a frame measures 38.5 kpc on a side for each panel. *Bottom six*: The same as the middle six but projected onto x-y plane. The position of each globular cluster *with respect to the center of the dwarf* is plotted and a frame measures 17.5 kpc on a side.

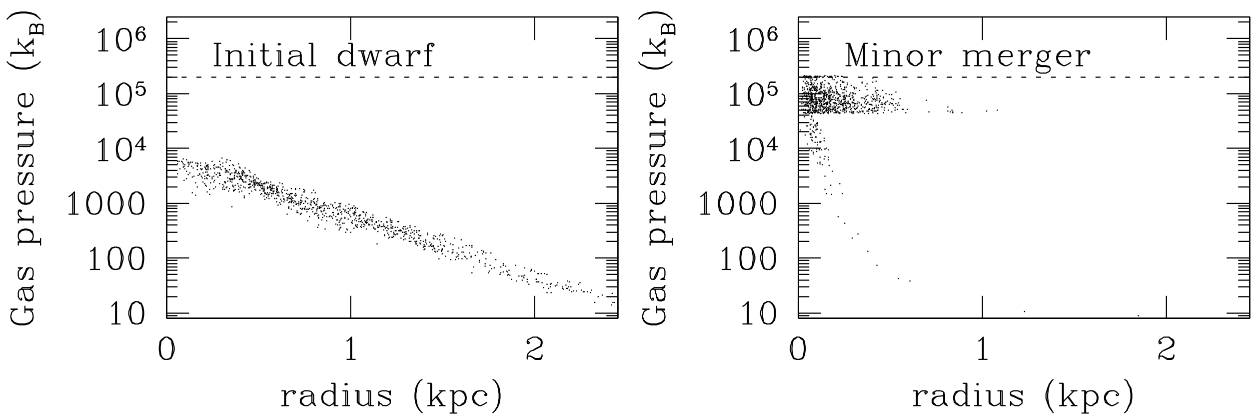

Fig. 2.— *Left*: Distribution of gaseous particles on a radius-pressure plane for the initial gas-rich dwarf model. The dotted line shows the threshold pressure over which globular clusters are assumed to be formed. *Right*: Distribution of particles that are *initially gaseous particles* on a radius-pressure plane for the fiducial model at $T = 0.56$ Gyr. Here the "radius" means the distance from the center of mass of the dwarf. Not only gaseous particles but also new stellar ones formed before $T = 0.56$ Gyr are plotted. For each new stellar particle, the gaseous pressure at the epoch when the precursor gaseous particle is converted into the new stellar one is plotted. Accordingly, by comparing the right panel with the left one, we can clearly observe how drastically global dynamical evolution of dissipative tidal interaction and minor merging has increased the gaseous pressure until $T = 0.56$ Gyr. Note not only that gaseous pressure become rather high during tidal interaction, but also that the gas is very strongly centrally concentrated at this epoch.

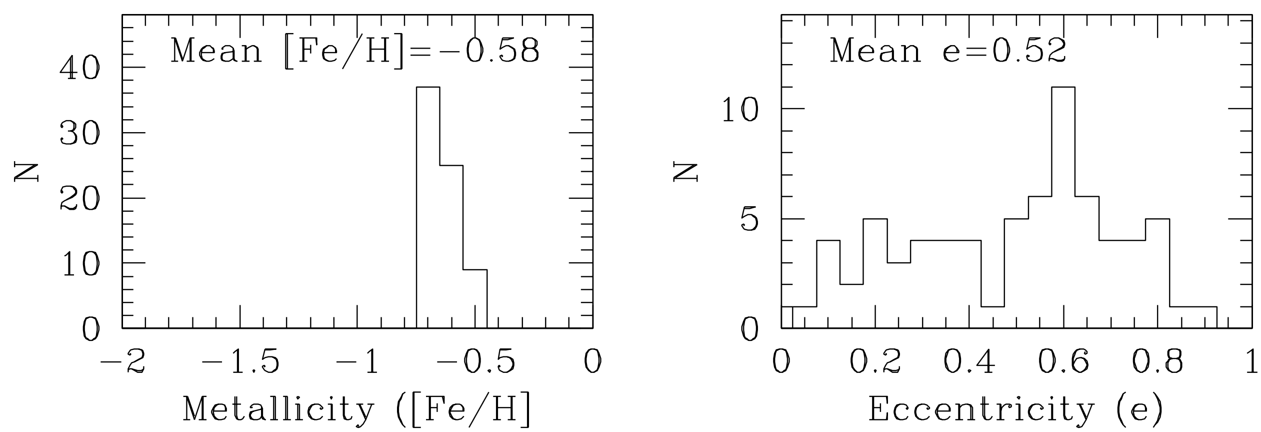

Fig. 3.— Metallicity distribution (left) and the distribution of orbital eccentricity e (right) for globular clusters formed in minor merging. Here e for each globular cluster is defined as $e = (r_{apo} - r_p)/(r_{apo} + r_p)$, where r_{apo} and r_p are apogalactic and perigalactic distances from the center of the simulated Galactic disk, respectively. Mean e and metallicity ([Fe/H]) are given in each panel.

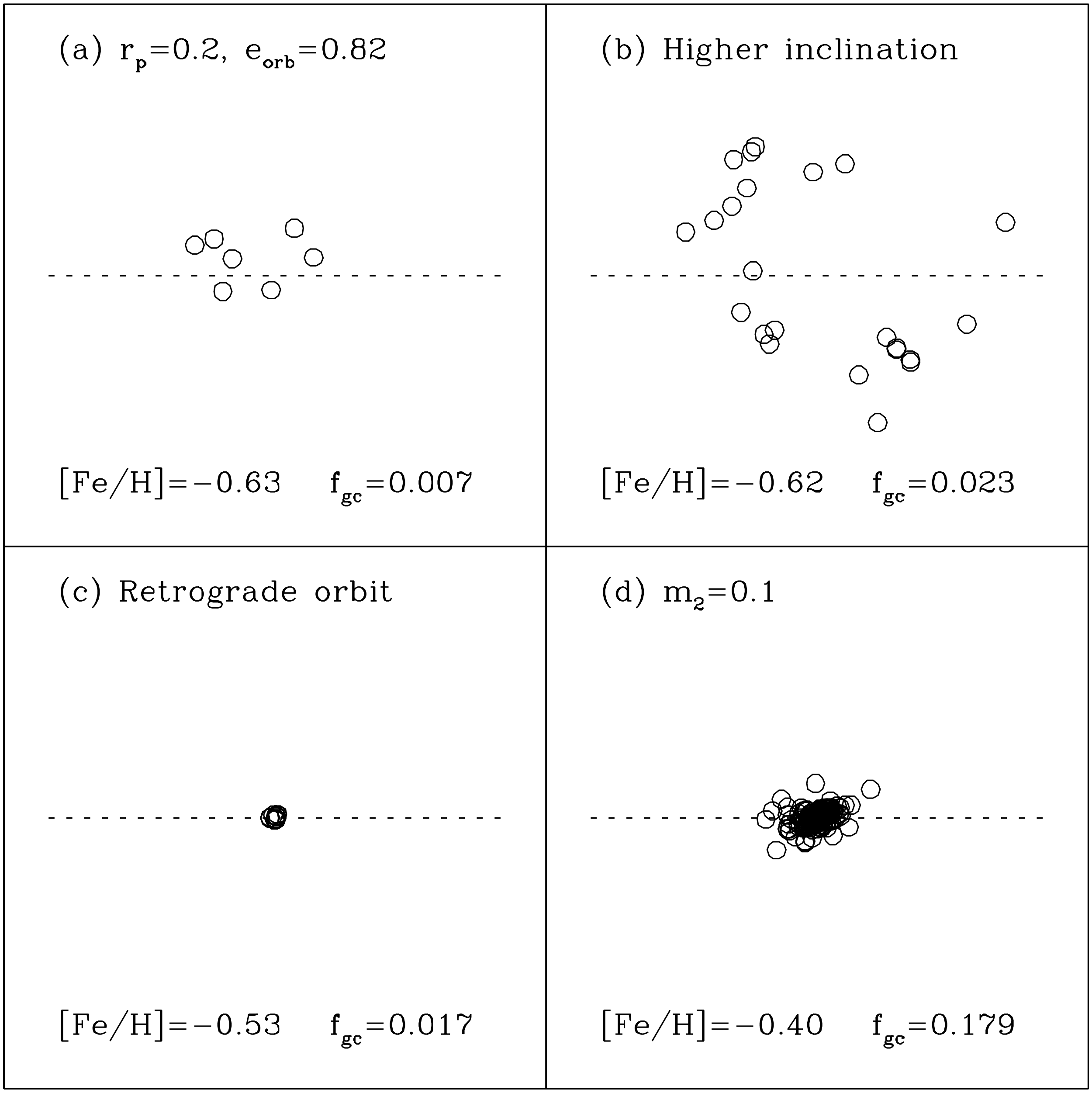

Fig. 4.— Distribution of the simulated globular clusters (represented by open circles) projected onto the x-z plane for (a) the model with smaller pericentric distance ($r_{\rm p}$ = 0.2 and $e_{\rm orb}$=0.82, upper left), (b) high orbital inclination (θ = 80°, upper right), (c) retrograde orbit (θ = 150°, lower left), and (d) larger mass ratio (m_2 = 0.1, lower right). A dotted line in each panel represents the position and the size of the initial disk. The ratio of the total number of the developed globular clusters to that of initial gas particles (represented by $f_{\rm gc}$) and the mean metallicity are given in the bottom of the panel for each model. This $f_{\rm gc}$ can represent the formation efficiency of globular clusters. For comparison, $f_{\rm gc}$ and mean [Fe/H] are estimated to be 0.071 and −0.58, respectively, for the fiducial model. Each frame measures 42 kpc on a side.

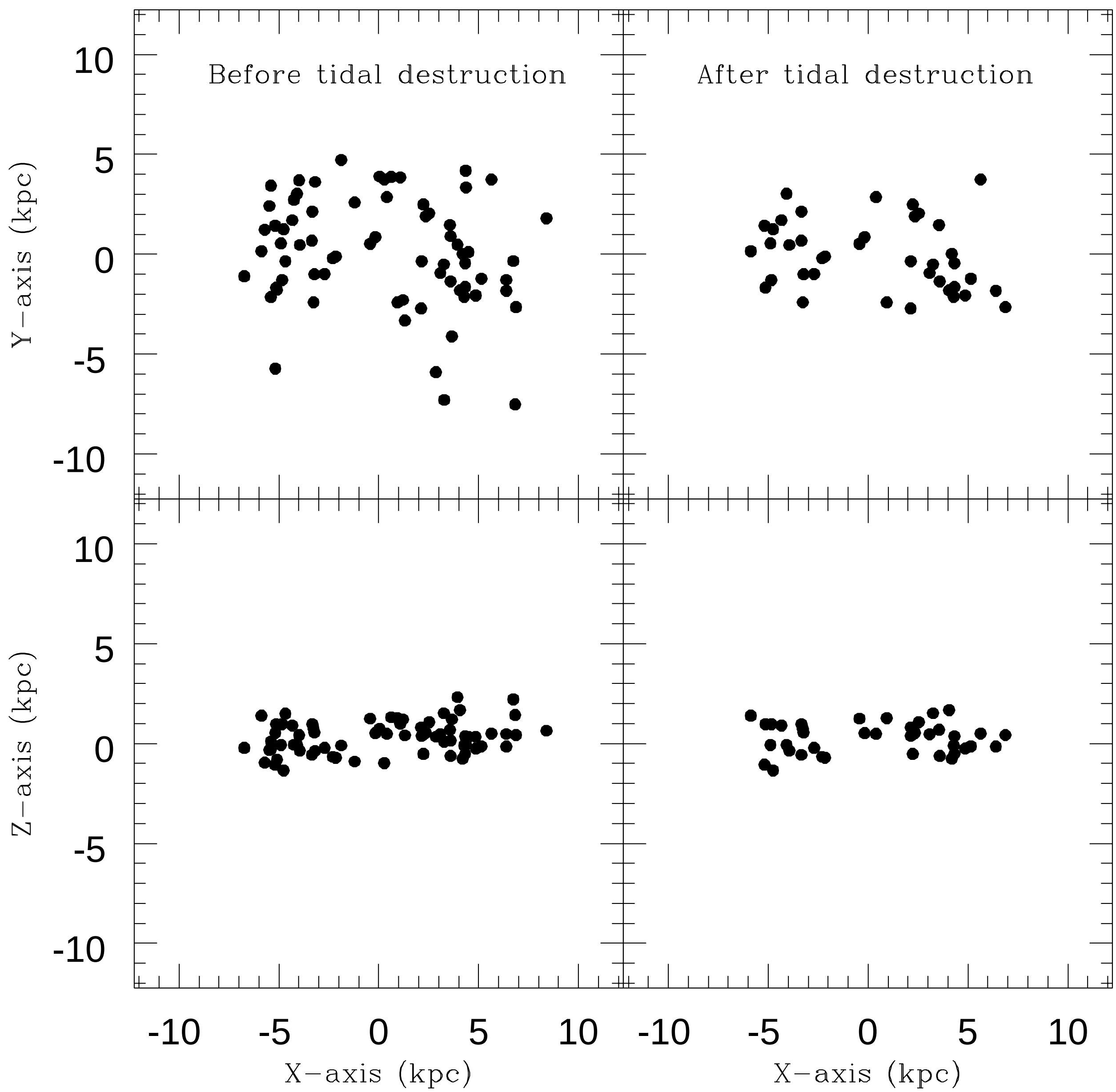

Fig. 5.— Spatial distribution of the simulated disk globular clusters at T = 3.95 Gyr projected onto x-y plane (upper) and onto x-z plane (lower), for all clusters (left two) and for the survived clusters after the removal of high-e clusters (with $e > 0.3$) having the pericentric distances smaller than 2 kpc (right two) in the fiducial model. Thus, the left two panels show the spatial distribution of disk globular clusters just after formation, whereas the right two ones show the spatial distribution of clusters that have survived from tidal destruction (see the text for more details). Note that even if we consider the tidal destruction effect, the distribution is not so greatly different between the two cases.